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TITLE: USING PHOTOCONDUCTIVITY TO IMPROVE IMAGE-TUBE GATING SPEEDS

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USING PHOTOCONDUCTIVITY TO IMPROVE IMAGE-TUBE GATING SPEEDS

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ABSTRACT

A technique using the photoconductivity of semiconductor and insulator photocathodes to improve image tube gating speeds is presented. A simple model applicable to the technique and a preliminary experiment are described.

The gating speed of photoelectric image tubes is strongly dependent on the sheet resistance of the photocathode. Datch and Ogle [1] have developed a mathematical model describing the propagation of electrical pulses applied to the perimeter of a circular image tube. The voltage at a given radius is found to be a function of t/R, where t is the time and R is the sheet resistance.

The use of semiconductor and insulator photocathodes is attractive for many applications because of their spectral response and photoelectric yield. However, typical resistivities of such materials are many orders of magnitude greater than those of metals. As a result, image tubes utilizing such photocathode materials can have unacceptably slow gating speeds. To combat this deficiency in speeds, various schemes can be employed to decrease the effective resistivity. A thin conductive film can be deposited under or over the photocathode, or special doping can be used. However, these techniques may not always be applicable. Chemical incompatibility, a less-than-ideal spectral response or a lower yield can reduce the appeal of such techniques.

It is the purpose of this paper to suggest the alternative of using the inherent photoconductivity of these materials to decrease their resistivities. The image tube photocathodes would thus be subjected to light from two sources: one from the event we are trying to record and one from a second source (e.g. a pulsed laser) to increase the conductivity and allow a faster gating speed. Such a technique would not be expected to significantly alter the intrinsic spectral response or photoelectric yield of the material.

The effect of the two sources on a hypothetical semiconductor or insulator is illustrated in Figure 1. Energy is plotted in the vertical direction with the pertinent energy levels noted: E_{VB} is the energy at the top of the nearly filled valence bands; E_{CB} is the energy at the bottom of the nearly empty conduction bands; $E_g = E_{CB} - E_{VB}$ (the band gap); and E_T is the emission threshold energy, i.e., the energy an electron must have to escape the photocathode into the vacuum. Electrons with energy E_T in the solid will have zero kinetic energy in the vacuum. For simplicity, we assume light from the source event is monochromatic, with photon energy, $h\nu_1$. With this photon energy, some source light will be absorbed resulting in photoelectrons with some kinetic energy (case a), while other electrons photoexcited by light from the source event will not have sufficient energy to escape the photocathode (case b). On the other hand, light from the second (primer) source has a lower photon energy, $h\nu_2$, which, when absorbed, can only result in electrons

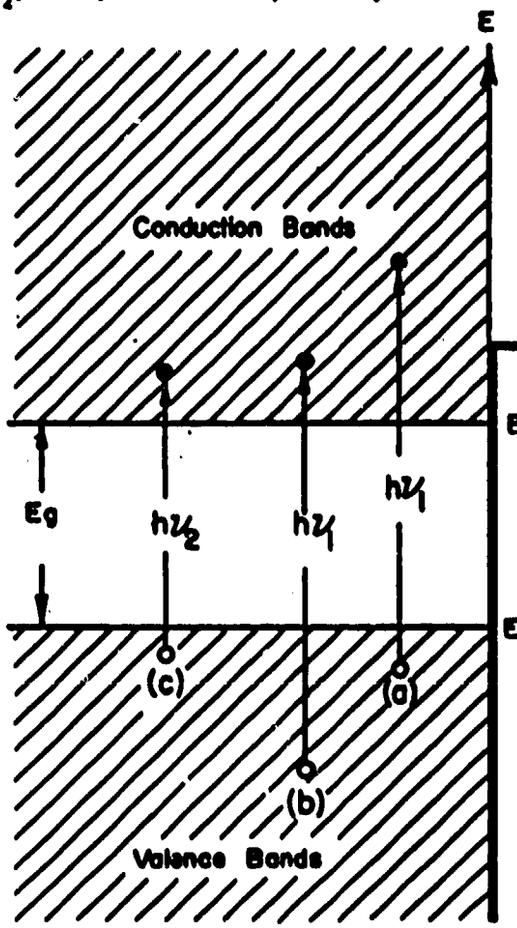


Fig. 1. Energy level diagram for a semiconductor or insulator. Shows emittation of electrons due to absorption of relatively energetic photons, $h\nu_1$, in (a) and (b), and less energetic photons, $h\nu_2$, in (c).

with energy less than E_1 (case c). Such electrons cannot escape the photocathode, but can contribute to increased conductivity. Analytically, $h\nu_2$ is constrained by $E_g \leq h\nu_2 < E_1 - E_{VB}$.

It should be noted, of course, that even if our primer source lies in the appropriate photon energy range, a small amount of photoemission will still occur. Absorption at higher lying impurity sites, two photon absorption or photoexcitation of electrons already in the conduction bands (for temperatures above absolute zero) can all contribute to a photocurrent even when $h\nu_2 < E_1 - E_{VB}$.

Generally the conductivity of semiconductors and insulators is directly proportional to the number of excess mobile carriers (i.e., conduction band electrons and valence band holes). Specifically,

$$\sigma = e(n_e\mu_e + n_h\mu_h), \tag{1}$$

where σ is the conductivity, e is the elementary charge, n_e and n_h are the respective conduction electron and valence hole concentrations, and μ_e and μ_h are their respective mobilities. Since mobilities are essentially unaffected by photoabsorption, an increase in n_e and n_h via photoabsorption will result in a corresponding increase in conductivity.

In order to determine a quantitative relationship between the primer source intensity and the conductivity, a simple photoconductivity model is assumed. It is assumed that every absorbed photon produces a hole in the valence bands and an electron in the conduction bands. Further, these electrons and holes will have identical mobilities, $\mu = \mu_e = \mu_h$, and lifetimes, τ. With an absorbed primer source intensity, I (photons/cm^2-s), the carrier concentration, n, is governed by

$$\frac{dn}{dt} = \frac{2I}{s} - \frac{(n-n_o)}{\tau} , \tag{2}$$

where n_o is the equilibrium (dark) carrier concentration (both electrons and holes), and s is the photocathode thickness. If a constant primer source, I, is applied at t=0, the solution for $t > 0$ is

$$n = n_o + \frac{2I\tau}{s}(1 - e^{-t/\tau}) . \tag{3}$$

The sheet resistance is given by $R = 1/\sigma s$, so we can write

$$R = \frac{R_o}{1 + 2I\mu\tau eR_o(1 - e^{-t/\tau})} , \tag{4}$$

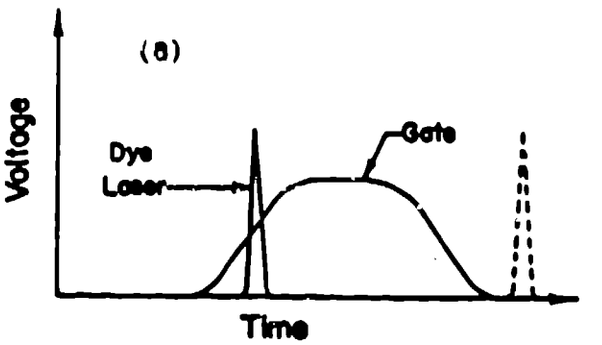
where $R_o = 1/n_o es\mu$ is the dark sheet resistance. As is clear from (4), R asymptotically approaches the value $R_o' = R_o/(1 + 2I\mu\tau eR_o)$ for $t > \tau$. When the primer source is removed, R will then decay exponentially to R_o with time constant τ.

A preliminary experiment testing this technique has been performed. The basic experimental set-up used has been reported,[2] but will now be briefly reviewed.

An electrical gating pulse is applied between the extractor and photocathode of the image tube, while a six-picosecond-wide FWHM dye laser pulse is presented to the full area of its photocathode. The relative timing of these pulses is depicted in the plots of Figure 2a. The delay between the two pulses is sequentially adjusted to walk the dye laser pulse through the gate. When the light pulse occurs before the gate, nothing is observed at the tube output. But as the light pulse is retarded to occur slightly after the onset of the gate, the tube begins to conduct (i.e., shutter open) nearest the perimeter of the tube. With a sufficiently wide gate pulse, continued retardation of the light pulse relative to the onset of the gate shows more and more of the tube conducting until finally the entire tube is fully on. The turn-off characteristics of the tube are then observed as the laser pulse is retarded past the end of the gate pulse.

For the current experiment, a primer source was added in the form of a Nd:Yag laser. Pulses from this laser were about 70 ns wide FWHM and centered on the dye laser pulse. The relative timing for this case is shown in Figure 2b. The average intensity of the primer source was ~ 95 W/cm^2, which, if it were all absorbed at the photocathode, would indicate I was about 5×10^{20} photons/cm^2-s.

The image tube used was a microchannel-plate intensifier tube with a S-10 photocathode. The S-20 has a photoelectric threshold of about 1.5 eV and a bandgap of about 1.0 eV.[3] The Nd:Yag laser has a photon energy of 1.17 eV ($h\nu_2$), while the visible light from the dye laser has a photon energy of about 2 eV ($h\nu_1$).



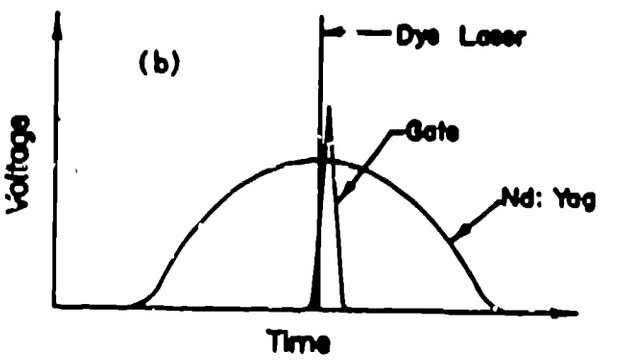


Fig. 2. (a) Timing of standard experimental set-up. Dye laser pulse is ~ 6 ps wide, while the gate is 1.5 ns or more wide. Dye laser pulse is sequenced from solid curve position to the dashed curve position during a measurement. (b) Timing with the relatively wide 70 ns Nd:Yag primer pulse added. The dye laser pulse is sequenced through the gate as in (a).

Consequently, the two sources fit the criteria illustrated in Figure 1.

The addition of the primer source resulted in no perceptible increase in gating speed. The time resolution for gating speed was ~ 100 picoseconds. For the tube tested this means that at least a 5% decrease in resistivity would have been necessary to have been detected.

The lack of a noticeable effect allows a calculation of an upper limit to the product, $\mu\tau$, for the S-20. Using the equations of Detch and Ogle [1], R_o is found to be $\sim 10^4\ \Omega$ for the tube under test. Assuming a 5% or greater decrease in R would have been observable, equation (4) with $t \gg \tau$ implies that $\mu\tau < 3 \times 10^{-8}\ cm^2/V$.

Values for neither μ nor τ could be found in the literature for the S-20. However a value of μ for the S-13 photocathode of 500 $cm^2/V\text{-}s$ [4] was found. The S-13 photocathode is somewhat similar to the S-20. Assuming that this value is also a reasonable estimate of μ for the S-20, this suggests that $\tau < 60$ picoseconds for the S-20.

In an attempt to observe some photoconductive effect, the primer pulse was focused to a spot about 0.5 cm in diameter. Though this increased I by a factor of 25 in this localized spot, still no change in gating response was observed. However now an image of the primer spot was observed at the tube phosphor. The corresponding current was measured to be about 10 nanoamps. Taking into account the microchannel plate gain of 400 and the duty factor, we infer the S-20 photocathode sensitivity to 1.06 micron radiation to be about 3×10^{-7} A/W (quantum efficiency 3.5×10^{-7}). This compares with a typical sensitivity of 6×10^{-2} A/W at 0.4 micron for the S-20 (quantum efficiency about .2).[5]

Further experiments can be performed to determine the usefulness of photoconductivity to improve gating speeds. With the S-20 microchannel-plate tube used in this experiment, there are two choices. First, since in this experiment the channel-plate gain was 400, one could use an event source and Nd:Yag primer source both 400 times as intense, and use a channel-plate gain of ~1. Then if, in fact, our value for μ of 500 $cm^2/V\text{-}s$ were correct, and if τ were as large as 0.15 picosecond, then a reduction in gating time could be observed. A second option would be to use a primer source of longer wavelength (lower photon energy) - as long as about 1.24 micron (1 eV). Since $h\nu_2$ would still exceed or match E_g, absorption could still be expected to be strong, but photoemission from this primer source would be considerably weaker than what was observed in the experiment described in this paper. A more intense primer source at this lower photon energy could then be used.

Other materials may prove to be better candidates for utilizing the concept presented in this paper. Wider band gap ($E_g > 2$ eV) materials can be appealing photocathodes for use in the ultraviolet and soft x-ray regions. Because of their larger band gaps they can be photoelectrically insensitive to visible light and generally have high quantum yields (~10%)[3].

The resistivities of such materials are high primarily because the large band gap severely restricts the number of thermally excited carriers at room temperature. However, their mobilities and lifetimes can be significant. A classic example is cadmium sulfide. Its band gap is 2.42 eV, so the dark conductivity is very low. Yet the carrier lifetime is on the order of milliseconds [6], and the electron mobility is on the order of 100 $cm^2/V\text{-}s$ [3].

In conducting a photoconductivity-assisted gating experiment on an image tube possessing a photocathode of CdS or similar material, one would not necessarily have to restrict the photon energy range of the primer source. One would only need $h\nu_2 > E_g$. With the long carrier lifetime, the primer source could be presented well before the gate and then removed a few microseconds prior to the gate. Photoemission due to the primer source during the gate would be eliminated, and the tube could be gated on and off before the conductivity decayed appreciably.

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